Marine Vortices and Their Computation

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Abstract

Some of the physics involved in marine vortices and their generation for surface ships and submarines is examined in this paper. Surface ships can generate bow, bilge, and stern vortices from the hull in addition to vortices from any appendages or protrusions, such as bilge keels and shafts. Submarines, with their axially symmetric hull forms, often have more benign flow fields than surface ships, but generated vortices can have a significant influence on the behavior of the vehicle. The ability to compute such vortical flows has advanced rapidly and progress that has been made in computing such flows with Reynolds Averaged Navier-Stokes (RANS) solvers is discussed. Some of the areas where RANS computations are being used for surface ships and submarines are described and an indication is given of where the naval community is in its ability to accurately predict these complex flow phenomena.

Introduction

For marine vehicles to move efficiently through water requires streamlined hull forms that offer a minimum of resistance so that the vehicles can be economically powered. In addition, surface ships must operate in calm and rough seas for long periods of time so the stability and motions of the ship in waves are extremely important and one must consider aspects such as crew and passenger comfort. Consequently, the study of vortices created by marine vehicles has often been secondary to other issues. The main interest in vortical flows has been to determine the inflow to the propulsor and any effect vortices have on it. However, there are always efforts to have more efficient vehicles, which may be achieved by reducing drag due to vortex generation as well as providing better propulsive efficiency. In addition, naval vehicles are going through significant changes due to stricter requirements and a shift in thinking to littoral warfare for various Navies. This may require alternative hull forms such as integrated propulsor/hull designs [1] as well as ships that meet new stealth requirements [2]. Because of this there is renewed interest in understanding and analyzing the details of the hydrodynamics of Naval vessels and more attention is being directed at the vortical flow fields generated by them.

A vortex in the marine environment is not necessarily any different than a vortex in general and turbulence, eddies and interactions make their study complicated. Indeed, various definitions of a vortex exist [3], but here we are describing a vortex as the rotating motion of a multitude of material particles around a common center as per Lugt [4,5]. This is only valid for a reference frame that does not move relative to the center of the vortex, but is adequate for the present discussion. Vorticity and vortices are related, but they are not the same thing. Vorticity must be present in a flow to generate a vortex, but there is not necessarily a vortex in a flow when vorticity is present. Additionally, the maximum vorticity in a flow is not necessarily associated with the location of a vortex in the flow. For homogeneous baratropic fluids vorticity is generated at surfaces and from there convected or diffused into the flow. As pointed out by Lugt [6] flow separation is necessary for the generation of vortices at solid walls where vorticity of the boundary layer is carried into the fluid in the form of a shear layer. The details of this separation process, which often involves the generation of secondary vortices and subsequent ejection from the surface, can be very complicated, Doligalski et al [6]. This review will discuss the dominant vortices generated by marine vehicles that are of traditional concern in naval hydrodynamics, which are those generated from the appendage/hull intersection and the hull in general.

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The prediction of such vortices traditionally relied on vortex methods, which were comprehensively reviewed by Sarpkaya [7]. These methods are primarily extensions to inviscid methods and require approximations to define the separation line and stream surface leaving the body or previous knowledge from experiments or observations. Without this knowledge Reynolds averaged Navier-Stokes (RANS) codes offer a possibility of predicting such flows to the level needed by designers and engineers. With increasing computer power tremendous advances have been made in their use over the past decade for the prediction of ship hydrodynamics, Gorski [8]. This paper will also review some of these efforts as they pertain to the prediction of marine vortices.

Surface Ships

Surface ships are rich in vortical flow. Because of the shape of a surface ship, due to requirements of roll stability and the necessity of operating in waves, there are many possibilities for flow separating from the hull and creating vortices. However, surface ships are streamlined so most of this separation occurs in the cross flow direction creating longitudinal vortices. In general, the flow is downward and outward over the forward section of the hull and upward and inward towards the stern. This can lead to various vortices including: bow, bow dome, bilge, and stern vortices as shown in Fig. 1. Other vortices can also exist depending on hull shape and local flow angle. Vortices can also be created at the air/water interface due to wave breaking at the bow of ships as well as at the stern of transom hulled ships, Lugt [9]. The flow will also separate from any sharp edges that are not parallel to the flow, which often occurs on appendages in operating conditions. Surface ships operate in a seaway where the buoyancy forces and moments due to the waves and interactions with the hull dominate. Because the forces generated by the rudder are relatively small a surface ship is often not maintained on a strict course, but allowed to respond to the waves. This changes the local flow angles and can significantly alter any vortical flow making their study even more problematic.

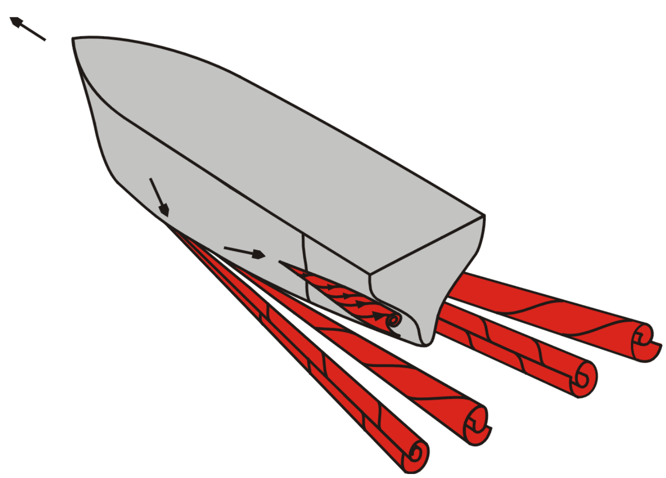

Fig. 1 Some surface ship vortices, from Lugt [9].

One cannot completely disassociate the study of ship vortices from waves and free surface effects. Due to the curvature of the free surface, as the bow of a ship is approached, a non-zero vorticity component is generated in the transverse direction. Additionally, a stagnation point occurs at the free surface bow intersection. This can lead to a vortex wrapping around the bow as observed by Kayo and Takekuma [10] for a ship model. They concluded that this bow vortex flow is similar to a necklace vortex around a wing-body junction. For blunt nosed ships this necklace vortex can be readily observed, Baba [11], and its strength is dependent on Froude number, bow shape and a strong interdependence with the bow wave. There have been various attempts to describe the mechanisms involved in the formation of this bow vortex (see for example Dagan and Tulin [12] or Patel et al [13]). However, for many naval

combatants the bow vortex is fairly weak and the liquid sheet attached to the bow and subsequent wave breaking is more significant as seen in the recent measurements of Dong et al [14].

Flow at the front of a ship tends to be downward along the walls with some of it flowing around the bilge and continuing downstream on the underside of the hull. Large turning around the bilge corner can create a bilge vortex, much like the leading edge vortex of a delta wing, which leads to increased resistance. The shape of the bow region can significantly impact this forward bilge vortex as illustrated by Takahei [15]. The free surface can also impact any vortices generated as the free surface can alter the local flow direction. As described by Tagori [16] there can be two sets of vortices generated from the bilge. At the stern of a ship the flow running underneath the hull comes upward and can separate at the bilge again forming longitudinal vortices. These vortices rotate in the opposite direction of those formed over the forward part of the bilge and are often more significant since they can flow into the propeller. There can also be an interaction between the bilge vortex and the propeller. This can cause the bilge vortex to change its location into the propeller disk as well as its strength [17]. In addition to the bilge vortex various hulls have a stern vortex that forms where the convex surface of the hull becomes concave [9]. Since the stern vortex rotates in the same sense as the stern bilge vortex the flow entering the propeller disk may actually be a combination of them depending on the particular hull shape. The vortical structure at the stern can become very complex with a main separation line along the hull or bilge where the flow first leaves the surface and possibly secondary separation lines depending on the strength of the vortex generated.

Hull shaping at the stern has a significant impact on the vortices generated by a hull, subsequent drag of the hull form, and the flow into the propeller. Surface ship hull forms have traditionally taken on the characteristics of a U or V section shape. The V shape hull forms are better for resistance, but they create an undesirable V shaped wake, and associated sharp nonuniformity, which enters the propulsor. The U shaped hull forms produce a large wake area increasing resistance, but provide more uniform, and thus favorable, inflow to the propeller. Consequently, a typical non-transom hull design is some combination of U and/or V shapes in an attempt to achieve balance between the increased propulsion efficiency with the U shape, due to better propeller inflow, versus the increased drag such a hull creates. Saunders [18] mentions how the longitudinal vortices formed at the bilge could enter the propeller resulting in violent changes in effective angle of attack on the blades. He goes on to say how at that time it was customary to design V shaped hulls in the afterbody region to prevent this from happening. The vortices entering the propeller can also impact the stern vibration of full stern ships, which was an early driver in trying to understand them [19], and poor wakes are still the main source of cavitation and vibration for many modern vessels such as high-speed ferries [20]. However, a bilge vortex entering the propeller disk is not necessarily a bad thing. A vortex will tend to smooth out the flow and can reduce any wake deficits convecting downstream from the hull or any appendages such as skegs. This smoothing of the flow by a bilge vortex into the propeller can be beneficial for cavitation and vibration as shown by Valkhof et al [21] for a bulk carrier. Vortex generators [22] were briefly discussed by Saunders as a possible means to improve the flow field into the propeller disc by altering the high- and low-velocity wake streams of a hull by creating longitudinal vortices parallel to the direction of flow. Various other efforts to change the flow field behavior about ship hulls have also been proposed, but most flow control for marine vehicles is done with hull shaping.

Because of the importance of bilge vortices there has been much effort directed at computing them. Two tankers in particular have received attention, the HSVA [23] and the KRISO KVLCC2 tankers. Strong bilge vortices have a distinctive hook pattern in the axial velocity contours at the propeller plane, as shown in Fig. 2 for the KRISO KVLCC2 from the experimental data of Van et al [24]. The HSVA tanker was the focus of a 1990 CFD workshop on ship viscous flows [25] where it was shown that computations could not adequately predict the flow. For predicting largely boundary layer flows simpler algebraic and two-equation models seem more than adequate. However, when predicting complex flows with separation and when the details of the flow field are needed they are often inadequate. For these tanker flows the simpler models could not adequately predict the distinctive hook shape at the propeller plane. At a 1994 workshop in Tokyo [26] it was demonstrated that the HSVA tanker bilge vortex could be predicted quite well with nonisotropic Reynolds stress turbulence models. This was reiterated for the KRISO KVLCC2 Tanker which was a validation test case for the more recent

Gothenburg 2000 [27] workshop on ship flows. Zero- and one-equation models could not reproduce details of the vortex and the correct hook shape. The two-equation k-ε model is too dissipative, even with highly refined grids. For the KVLCC2 tanker it seemed full Reynolds stress models were needed for good predictions of the flow. Deng and Visonneau [28] concluded that while nonlinear two-equation models could do better for this flow than the basic two-equation models, only solving the full Reynolds stress transport equations would accurately predict this strong vortex flow since the local equilibrium assumption, which the simpler models are based on, is not valid. It is difficult to form firm conclusions about what turbulence models should be used. Simpler zero-, one-, and two-equation models seem to do well for predicting much of the flow field, particularly in regards to boundary layer development. However, if one needs details of a complicated flow, such as a strong vortex, the higher order models seem to be necessary. Although the Gothenburg 2000 workshop pointa toward full Reynolds stress models being needed for some complicated details, the simpler realizable and nonlinear two-equation models may provide the necessary accuracy for many problems. More details on the current state of RANS predictions for ship flows can by found in Gorski [8].

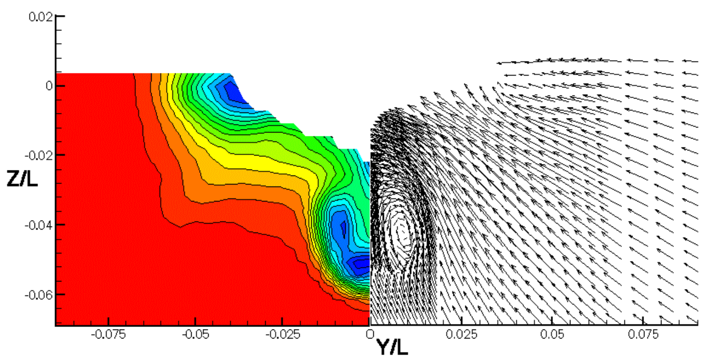

Fig. 2 KRISO KVLCC2 measured velocity at the propeller plane, Van et al [24].

A vortex associated with a bow bulb can also be generated at the bow. Bulbous bows exist on many ships as a way of decreasing wave resistance. At high speed much of the resistance of a ship is due to wave making. At these speeds a large component of the wave drag is generated at the bow from the creation of a bow wave. Bulbous bows were developed as a means of reducing the bow wave and associated drag. As described by Saunders [18] the first bulbous bow was designed by D. W. Taylor and incorporated on the U. S. battleship *Delaware* in 1907. Later, Wigley [29] developed the basic theory demonstrating how the flow accelerating over the bulb creates a low pressure region which interacts with the pressure field over the bow to partly cancel the bow wave and thus reduce the wave making resistance. The bulb needs to be designed such that the wave drag reduction is greater than the increase in drag associated with the added form drag of the bulb and the frictional resistance due to increased wetted surface area. A bow bulb can also reduce the forward bilge vortex as demonstrated by Takahei [15] who showed results for a bow with a bulb that created almost no vortices over the forward part of the bilge. Landweber and Patel [30] also described, based on the experiments of Hoffman [31], how the presence of a bow bulb can affect the strength of the bilge vortex.

For modern high speed naval combatants with transom sterns, bilge vortices are not the issue they are with tankers and bulk carriers. For example, flow around the bare hull version of DTMB Model 5415, which is an early version of DDG-51, has been measured and computed extensively as a CFD validation database [32,33] test case. The dominant flow feature is a vortex created at the sonar dome that flows downstream to the propeller plane. This flow was also a test case for the Gothenburg 2000 workshop. In general, since this vortex is not as strong as seen with the previous bilge vortices, RANS computations with two-equation models can predict this vortical flow well. The exact position and strength of the vortex, which depends on grid resolution and turbulence modeling, are not necessarily obtained, but enough detail of the average inflow and wake deficits for propeller design are obtained. At full scale the vortex will be closer to the hull and may or may not impact the propeller significantly. Additionally, the shafts and struts influence the flow into the propeller. For an integrated propulsor/hull

design (Rood [1]) these sonar dome vortices can directly enter the propulsor. For example, shown in Fig. 3 is the computed axial velocity contours for a generic integrated propulsor/hull form where the sonar dome vortices flow unobstructed into the propulsor.

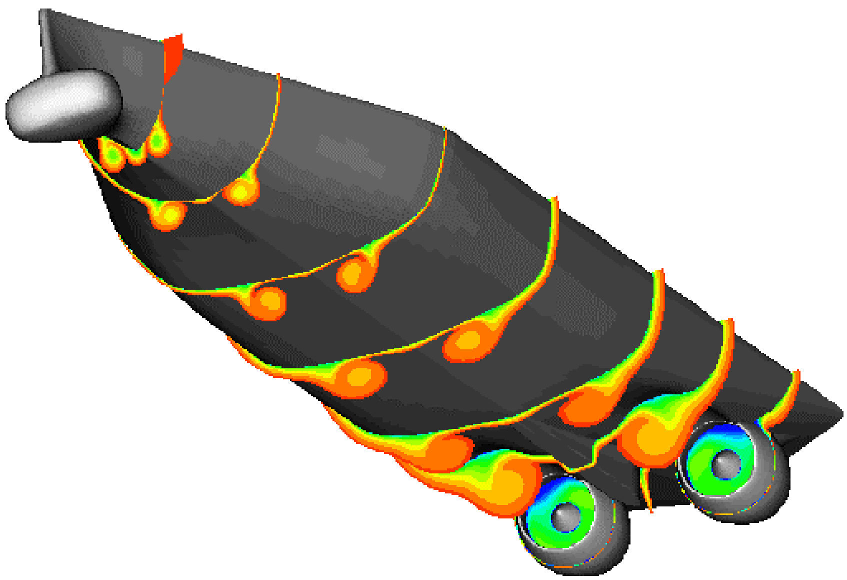

Fig. 3 Computed axial velocity contours for generic hull form.

Vortical flow also has a significant impact on the roll motion of a ship, which is largely influenced by viscous effects. This includes the drag on the hull form as it rolls and the flow separation from the bilge and keel where subsequent vortex formation can account for a large amount of the roll damping. Bilge keels will significantly increase the damping of roll motions as well as generate a lift force if any forward motion of the ship is present. Predicting roll effects analytically has been problematic because of the significant viscous effects. As demonstrated by Sarpkaya and O'Keefe [34] bilge keel damping is a result of the vortices shedding from the edge of the keel and the use of damping coefficients from flat plate tests in a free stream are not necessarily accurate for wall bounded bilge keels. Consequently, including roll effects in flow predictions has been largely empirical based, requiring numerous model scale tests to properly define coefficients that describe the roll motion. Model scale coefficients do not necessarily relate well to full-scale behavior due to the differences in Reynolds number. Roll motions are an ideal area to pursue viscous calculations methods including the Navier-Stokes equations. Yeung et al [35] show some promising results recently in this regard, though limited to two-dimensions. It is expected that studies involving the viscous computation of three-dimensional ship roll motions will receive more attention in the future.

Submarines

Early submarines spent much time on the surface and dealt with many of the same issues as surface ships, but modern submarines spend most of their time submerged. Burcher and Rydill [36] point to the *Albacore* and *Skipjack* classes as being major milestones in submarine development as these were the first shapes based on bodies of revolution that increased submerged performance at the expense of surfaced capabilities and are actually more like airships in their behavior. Conventional submarines are basically axisymmetric bodies with appendages and inherently produce weaker vortices than surface ships. However, because of the streamlined shape the vortices generated by the submarine can have a greater effect on its performance. For submarines acoustics is also very important and large vortices or flow separations can contribute to noise generation which is undesirable. Shown in Fig. 4 is a computed flow field about a submarine with pitch and yaw. Vortices typically consist of necklace vortices from

hull/appendage junctions, tip vortices from the appendages, and vortices generated directly from the hull due to angles of attack. Additionally, other protrusions from the hull exist that can generate vortices which include wide aperture arrays, towed array housings, and chin domes. Any protrusions from the surface will tend to increase the drag, due to pressure gradients, increased wetted surface area, and energy spent in vortex generation. The drag and subsequent power required to drive a submarine are important considerations in its design. The vortical flow generated from the hull and appendages can also significantly influence the maneuvering characteristics of a submarine. Such vortices also impact inflow to the propeller and the spatial distortions imposed by any generated upstream vortices are critical in its design.

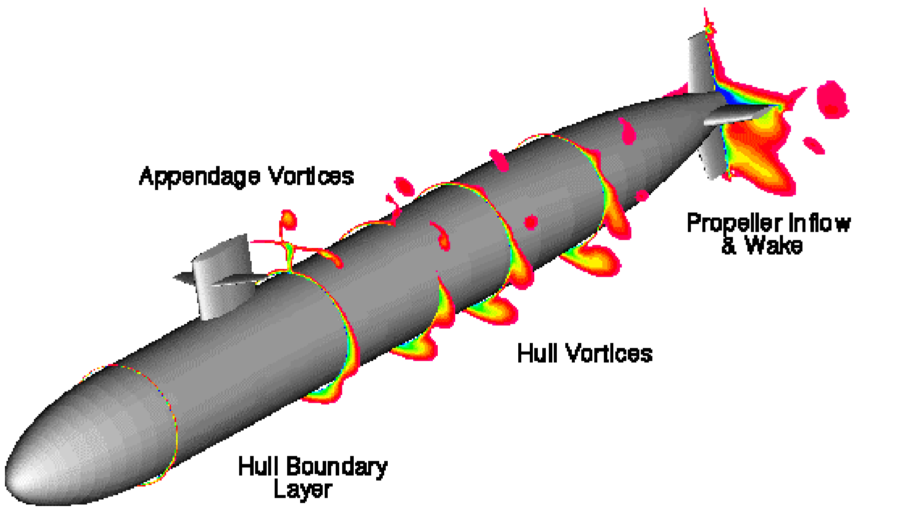

Fig. 4 Computed axial velocity contours for a submarine configuration at pitch and yaw.

Appendages provide an opportunity for vortices to be generated which can impact drag and quiet operation. It is well known that at an appendage/hull juncture a necklace vortex can form that wraps around the appendage and produces longitudinal counter rotating vortices that flow downstream. The generation of this vortex will add additional drag and can also negatively impact the flow into the propeller. Leading edge fillets, or strakes, can reduce the adverse pressure gradient at the leading edge of an appendage/hull juncture and reduce the vorticity in the longitudinal vortex formed in its wake, Simpson [37]. Shown in Fig. 5 are surface streamlines on the hull at an appendage/hull juncture with and without a leading edge fillet. For the case without the fillet separation occurs in front of the leading edge and one can clearly see the computed limiting streamline demarking the necklace vortex and the flow turning around the appendage. With the fillet present there is no clear limiting streamline or separation in front of the appendage leading to less drag. The largest appendage on any submarine is usually the sail and one can look at a recent edition of *Janes's Fighting Ships* [38] to see that the U.S. Navy has gone to leading edge fillets for its sails. Here pictures of the *Ohio* and *Los Angeles* class submarines have no leading edge strake on the sail, but the *Seawolf* sail has a large leading edge fillet as does the artist's rendition of the *Virginia*.

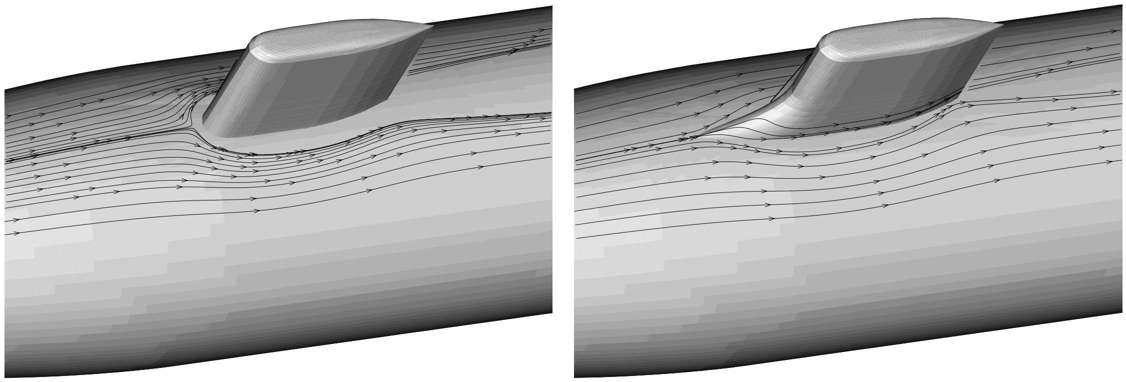

Fig. 5 Surface streamlines for a sail with and without a leading edge fillet.

Even with the addition of a leading edge fillet there will still exist longitudinal vortices downstream of the sail. This pressure driven secondary flow, also referred to as secondary flow due to curvature, is a result of the flow turning around the sail. As the boundary layer on the hull approaches the sail transverse vorticity is generated in the hull boundary layer. As the flow streamlines curve around the sail a longitudinal component of vorticity develops which flows downstream around the sail producing a pair of vortices similar to the necklace vortex of a wing/body junction. However, because of the leading edge fillet there is no leading edge separation and the vortex formed is significantly weaker than that achieved with no fillet. This can also be seen for large streamlined sails [39], as shown in Fig. 6, which must be designed to minimize the drag penalty associated with their larger wetted surface area. For the sail shown in Fig. 6 there is no necklace vortex formed as the streamlines flow smoothly over the hull and sail. However, as shown by the vector plot downstream of the sail there exists a pair of longitudinal vortices similar to what would be seen for a necklace vortex. These vortices are formed from the flow turning around the sail as just discussed.

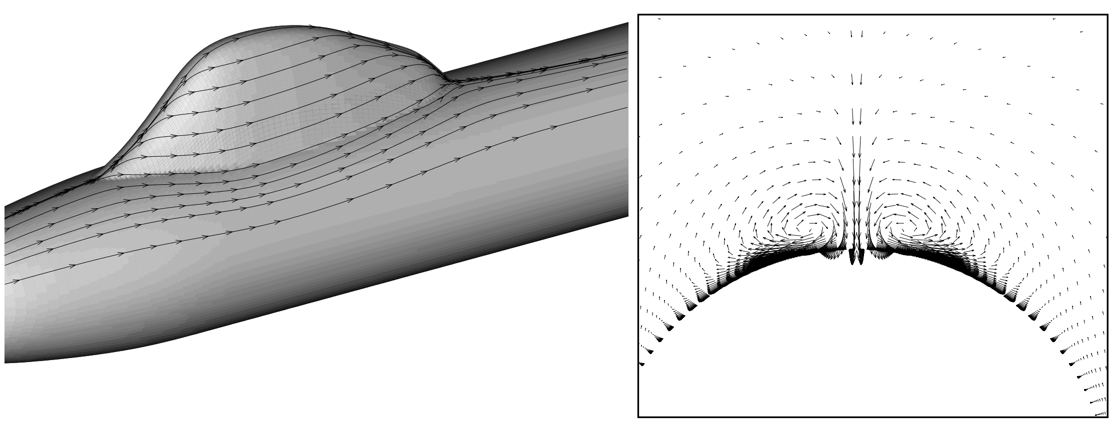

Fig. 6 Surface streamlines and downstream velocity vectors for a large sail.

Downstream of the sail is a stern appendage suite for maneuvering control. Again a necklace vortex can form at the base of each of these appendages when no leading edge fillet is present. This can lead to the secondary flow patterns embedded in the hull boundary layer downstream of a cruciform stern shown in Fig. 7. This vortical flow will cause high momentum fluid to be pulled down toward the hull immediately behind the appendages and low momentum fluid from the hull to be pushed radially outward

away from the appendages. It may not be possible to add leading edge fillets to the stern appendages as they may need to be moveable for maneuvering purposes. Even more complex is the flow field generated when dihedrals are present as shown in Fig. 8. Here the dihedrals and stern planes have leading edge fillets whereas the upper and lower rudders do not. The upper quadrant flow is similar to the straight cruciform design, but the flow in the lower quadrant is extremely complicated as the necklace vortices from the lower rudder interacts with the flow around the dihedrals.

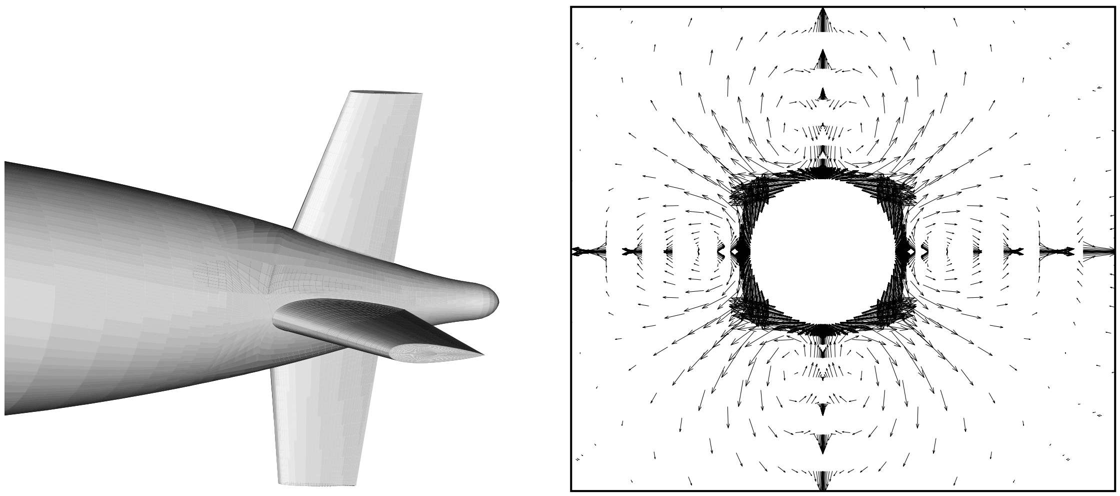

Fig. 7 Secondary flow behind a cruciform configuration.

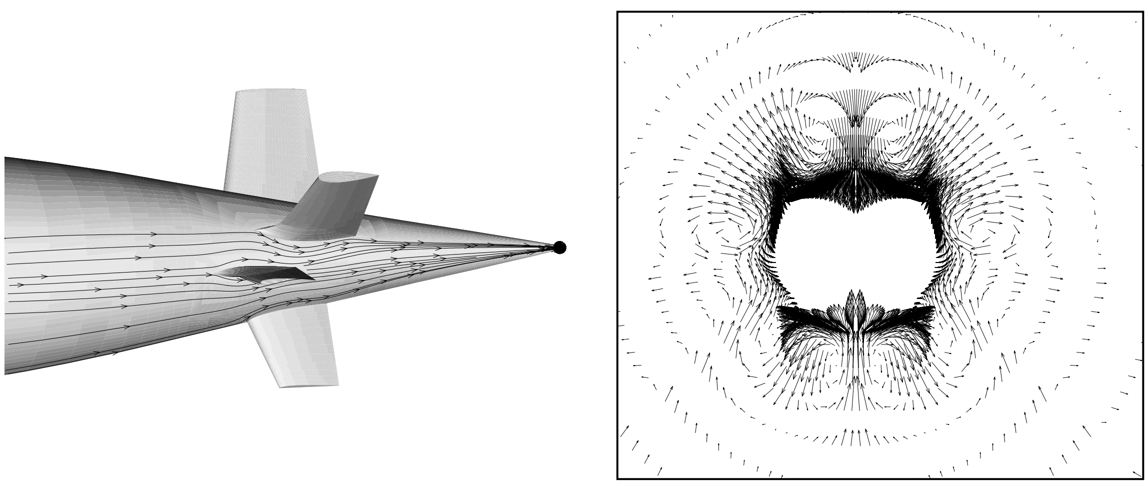

Fig. 8 Secondary flow behind a stern with dihedrals.

For straight ahead operations the major vortical flows are from the appendages. During maneuvers the angles of attack increase the cross flow velocity leading to flow separation on the leeward side allowing boundary layer vorticity to leave the hull surface and convect downstream as described by Saunders [40]. This is the classic three-dimensional flow separation from a body at angle of attack where a primary vortex will form with various secondary vortices forming depending on strength of the primary vortex. This cross flow separation is characterized by circumferential pressure gradients where the low pressure on the leeward side, as compared to the windward side, will produce an “in-plane” force and moment on the hull which can be significant. The appendage forces are usually larger than those generated by the hull vortices, but the hull vortices can influence maneuvers as they change the local angle of attack on the stern appendages inducing uncharacteristically large lift forces and roll moments. For actual maneuvers the flow is even more complicated since a submarine experiences different local angles of attack over the length of the hull which can be extremely different. For example the side flow

can be from port to starboard over most of the hull, but from starboard to port on other parts of the hull. Thus, the leeward side of the hull changes its position from bow to stern. Furthermore, submarines are not axisymmetric bodies that make perfect turns. The sail in particular creates asymmetric flow and leads to a healing motion during a turn as well as a tendency to pitch. Consequently, the flow separation from the hull is asymmetric which affects "in-plane" forces and can create large "out-of-plane" forces that can make maneuvers difficult to control and predict. The hull vortices during a turn can also significantly influence the propeller generating unsteady forces which also affect the maneuvering.

Multivortex [41] methods have been used successfully for predicting such flows. The drawback of such vortex methods is that the separation line where the flow leaves the body must be specified based on experience, experimental data, ad hoc assumptions, or a combination of the above. Accuracy of the prediction is directly dependent on how accurate the separation line is specified, which is usually changing in time for actual maneuvers. Consequently, maneuvers are often predicted with coefficient based approaches that are heavily reliant on experimental data. Sarpkaya [42] relatively recently recommended that the prediction of unsteady maneuvers of large bodies was best left up to the use of vortex and panel methods. When the problem is well defined with a large experience base these methods have provided worthwhile results and will continue to do so. However, whenever one starts investigating a new type of design without a large data base these methods are suspect.

Obviously, RANS based methods cannot compete with such inviscid methods in pure speed of getting answers, but they do offer at least the possibility of being less reliant on apriori knowledge. RANS computations of submarines have not received quite as much attention as surface ships due to the smaller community involved with them. Perhaps the first fully appended submarine RANS calculation was done by Gorski et al [43] for the SUBOFF configuration. The SUBOFF configuration is an axisymmetric model with various appendage components that was extensively measured [44] to provide a data-base to test CFD methods. At the time of the SUBOFF program it was shown that RANS calculations could predict the pressures quite well and some of the mean flow, but generally under predicted the strength of necklace vortices. Thus, they did not predict inflow to the propeller with the fidelity desired. Since that time there have been considerable efforts directed at submarine calculations, but the flow solvers and turbulence models are largely the same as they were a decade ago. The big difference with more modern RANS codes is they take advantage of the larger parallel computers and provide calculations on much finer grids than at that time. The finer grids can provide better flow predictions. However, predicting detailed flow into the propeller may still be an issue, depending on how much detail is needed, as seen from the complexity of the flow in Fig. 8. As already discussed for the bilge vortex full Reynolds stress models appear to be needed to accurately predict its details. Even when predicting the flow over a wing/body junction RANS codes have difficulty producing the vortex strength and location to a high degree of fidelity let alone in the context of a full submarine calculation. However, RANS codes are accurate enough and have matured to a point where they can be used for submarine design [45] and can be used very effectively to show trends, as demonstrated by Sung et al [46] for leading edge fillets. Calculating the complicated flow about full subroutines is becoming more routine and complete configurations are being done [47] which include a full ensemble of external geometry modifications. Because of the importance of vortical flow to submarine maneuvering and the problems of using inviscid methods for the prediction of such flows there has been a significant amount of effort to apply RANS codes for maneuvering submarines. This includes efforts to evaluate the forces during a constant turn [48], similar to rotating arm tests, as well as complete maneuvering calculations with moving appendages and propellers [49]. It still remains to be seen how accurate such calculations are. Simple maneuvers should be predictable. However, predicting highly complicated motions, where upstream hull and appendage vortices interact with the downstream appendages and propeller, may be difficult to predict, since accurately computing the vortical interactions in time will depend on good grid resolution and turbulence modeling and may be beyond current RANS capability.

Conclusions

Vortices have always been a part of Naval hydrodynamics. A large complex geometry cannot move through the water without creating vortices. Because of the streamlined shapes the vortical flow

field has often been of secondary importance to other more global effects. However, because of the impact such vortical flow has on the inflow to propulsors and their influence on the maneuvering characteristics of marine vehicles vortices have received considerable attention in naval hydrodynamics. With new requirements on platforms there is an even greater need for better understanding of the flow physics associated with Naval vehicles. In fact, recently the Naval Studies Board of the National Research Council recommended that naval hydrodynamics should be designated a National Naval Need in the United States [50]. The board also recommended more focus on long-term research of fundamental problems including vortex dynamics unique to naval surface and submarine vehicles.

Of significance over the last decade is the increased emphasis on the use of computational tools to evaluate these flows. In particular, with the advent of parallel computational capabilities, viscous RANS simulations have seen a larger role in predicting these flow fields. The shift to a more computational based design and analysis approach leads to the possibility of better designs in a shorter amount of time. Such computations allow for the rank ordering of designs as well as providing the entire flow field, which can lead to better understanding of the flow physics. There have also been recent efforts to obtain better experimental data to more adequately evaluate the flow physics for comparisons with the computations. This combination of computations and experiments will lead to our best chance of success in understanding and improving ship hydrodynamic flow fields. All these efforts show that it is an exciting time for viscous computations of marine vehicles, a field which has always had significant viscous/vortical flow physics, but has traditionally relied on inviscid computational techniques and experimental evaluation for design and analysis.

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Paper: 24
Author: Dr. Gorski

Question by Dr. Korner: You are especially interested in resistance or say drag of the ship. What is the relative size of the different parts of the drag of a submarine, e.g., wave drag and viscous/vortex drag?

Answer: There is only a small amount of wave drag. The major part is viscous drag.

Question 2: Why do you then argue – you say it on your first viewgraph – that viscous and vortex-flow effects are of minor importance.

Answer: We get the resistance from an overall evaluation and model tests. Details of viscous/vortex flow have not been considered.

Question by Dr. Bulgarelli: Could you make some more comments on the boundary conditions that you must consider in order to take into account free surface and waves on ship vortices?

Answer: In our computations only the water portion of the flow field is solved for. The free surface is treated as a material boundary with a kinematic condition to describe it. Standard dynamic inviscid boundary conditions are applied at the free surface for the Navier-Stokes equations. Consequently, the grid has to change, both on and below the free surface, as the solution evolves, which is the main drawback of this approach, but it has yielded some very accurate free surface predictions.

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